A noise reduction using signal-subspace method

M. Kawakatsu[1], K. Kobayashi[1], Y. Uchikawa[2], M. Adachi[3], M. Saito[3], and M. Kotani[3]

[1]Applied Superconductivity Research Laboratory, Tokyo Denki University, 270-1382, Chiba, Japan; [2]College of Science and Engineering, Tokyo Denki University, Saitama, Japan; [3]College of Engineering, Tokyo Denki University, Tokyo, Japan

1 Introduction

In the biomagnetic measurement performed in laboratory, the biomagnetic signal is extremely weak compared with environmental magnetic noise. To reduce signal to noise ratio there are several representative noise reduction methods both in hardware and in software such as the use of gradiometer, averaging, filtering, principal component analysis (PCA) method [1], and signal-space projection method (SSP) [2]. The PCA method is based on the fact that the first component of PCA for non-averaged data is irrelevant to evoked fields. On the other hand, the SSP method removes a noise vector known a priori. (For example, eye movement, train, and vibrations).

However, these two methods may drastically reduce the signal when the orthogonality of noise and signal in the sensor space is bad, even if the S/N ratio is large. To overcome this difficulty, we propose the method of estimating the subspace spanned by the sensor outputs. It is estimated from the lead-field vectors for the uniformly distributed lattice points in the head. It has been shown by simulation that projection of the measurement to the signal subspace reduces the noise effectively.

2 Methods

For designing a noise reduction method, two conditions were assumed on magnetic signal sources; (1) there is a number of localized sources, (2) noise components come from outside the head.

2.1 Lead-field

The lattice points for calculating the lead-field, are positioned in the sphere that approximate the head. They were placed in the 1cm interval. If the geometrical configuration of the head and sensor array is given, we can easily calculate the lead field vector $\mathbf{L_i}$. The i indicates the lattice point number. The lead-fields, $\mathbf{L_i}$ are calculated for dipole θ and φ direction, at each points by Sarvas's equation[3].

2.2 Signal subspace

Let us denote by $\mathbf{S_S} = \mathbf{R}^{195}$ the set of the signal space vectors consisting of the output from sensors, and by $\mathbf{S_L}$ a set of the lead field vectors between sensors and the lattice points. The $\mathbf{S_L}$ is derived by applying PCA with lead field matrix $\mathbf{L}=\{\mathbf{L_1}, \mathbf{L_2}, \text{---}, \mathbf{L_M}\}$, where M is the number of the sensor. The set $\mathbf{S_L}$, therefore, is the subspace of the set $\mathbf{S_S}$. In this case, we determine that $\mathbf{S_L}$ is composed by accumulated proportion of the 99.9%. The filtered fields **B*** are finally calculated by the following equation;

$$\mathbf{B^*} = (\mathbf{B} \bullet \mathbf{S_L})\mathbf{S_L} = \sum_{i=1}^{N'} (\mathbf{B} \bullet \mathbf{e_i})\mathbf{e_i} \quad (1)$$

B is the measured magnetic fields, $\mathbf{e_i}$ and N' the ith eigenvector and the number of eigenvector of $\mathbf{LL^T}$ for accumulated proportion of the 99.9%, respectively. The number of eigenvector N' is usually 40 - 50.

Since this method, assumes the signal space is advance, the signal component would not be reduced.

2.3 Simulation

This method was applied to simulation data. The signal is assumed at [6.2, -0.2, -0.6] cm in the head, with moment [8, -2.5, -39.0] nAm. The sensor output is shown in figure 1.

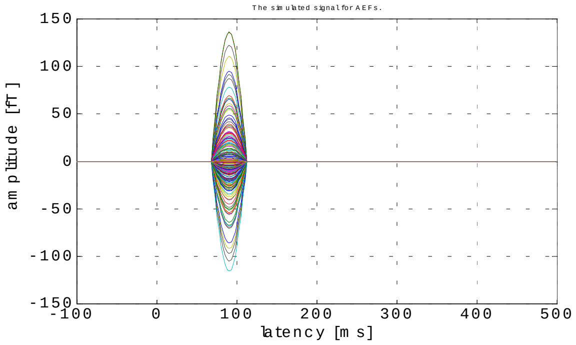


Figure 1. *The simulated signal.*

Actual measurement field in the shielded room are added as noise having three noise levels. The three noise levels were obtained by averaging the field 50, 20, and 10 times for each 1.2s epoch. The noise level is designated 1,2, and 3 in the decreasing order of the averaging number.

2.4 The MEG measurements

The measurements were carried out with a whole-head 195-channel SQUID MEG system for detecting vector components [4]. The system has 65 detection sites, each site containing three gradiometers which are perpendicular to each other. The typical system noise in the magnetic shielded room is 10fT/√Hz.

The subjects were 3 right-handed male (22-30 years old). The stimuli were 1 kHz tone bursts (duration 100ms, rising and falling time 10 ms) to the right ear. The inter stimulus interval is 900ms.

The condition of the data acquisition is as follows. (1) Sampling frequency 400Hz, (2) Analog band-pass filter 0.1-100Hz, notch filter 50Hz, (3) Digital band-pass filter 0.5-40Hz, Baseline –100-0 ms.

We applied the method to AEF data, averaged 100, 50, 20 times. And, we applied to 10 sub-averaged data, by shifting 10 epochs (1-20th epoch, 11-30th, …, 101-120th epoch).

3 Results

3.1 Simulation data

In order to examine its effectiveness, the method was applied to the field from the current dipole positioned at x=-0.5~0.5[m], y=0 [m], z=0.01[m] (Figure 2(a)). The noise reduction ratio defined as follow.

$$rr = \|B^*\| / \|B\| \qquad (2)$$

Here, $\|A\|$ is the L_2 norm of A. It is seen in figure 2 that the method functions as an effective spatial filter in x-y plane, but provides almost no reduction for the negative z direction.

The waveforms before and after applying this method to the simulated data contaminated by a noise with noise level 1,2, and 3 are shown in figures 3-5.

The mean reduction ratio is defined by.

$$mrr = (\sigma_{after}-\sigma_{before})/\sigma_{before}*100\ [\%] \qquad (3)$$

The σ_{before} and σ_{after} are the averages of the standard deviations of the field in the baseline with all channels for before and after applying the method. The mean reduction ratio for the noise level 1-3 are about 21.6±0.8 % (mean±SD), 22.9±2.7%, and 23.1 ± 2.7%, respectively. The errors in position estimation of the ECD's are shown in table 1. The errors are shown to be decreased by proposed method.

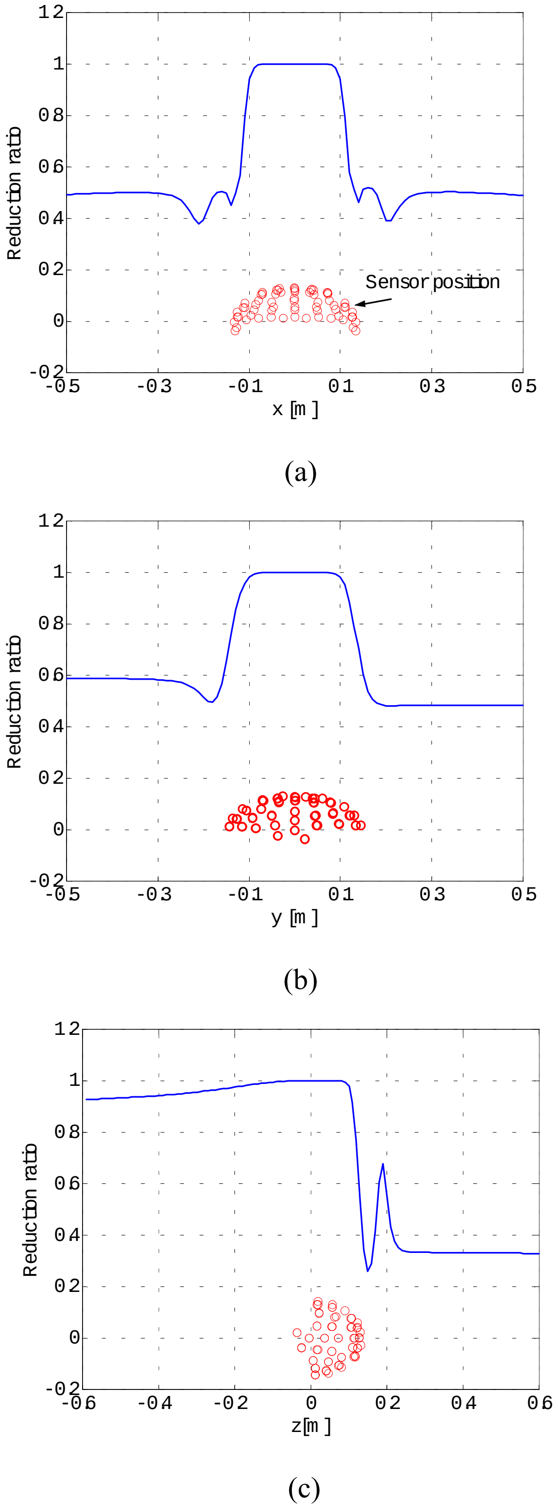
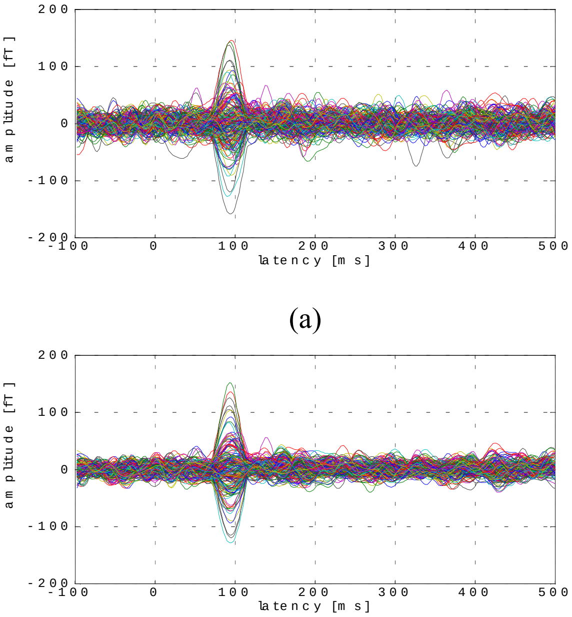


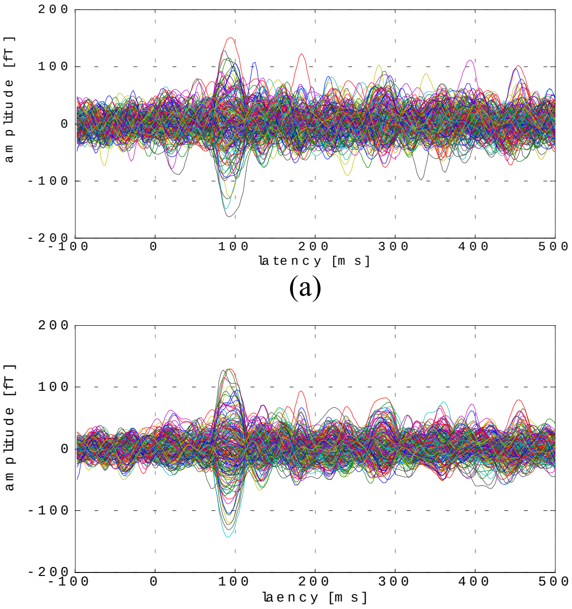
Figure 2: *The reduction ratio for a dipole for (a) x=-0.5-0.5[m]. , (b) y=-0.5-0.5[m], (c) z=-0.6-0.6[m]*



(a)

(b)

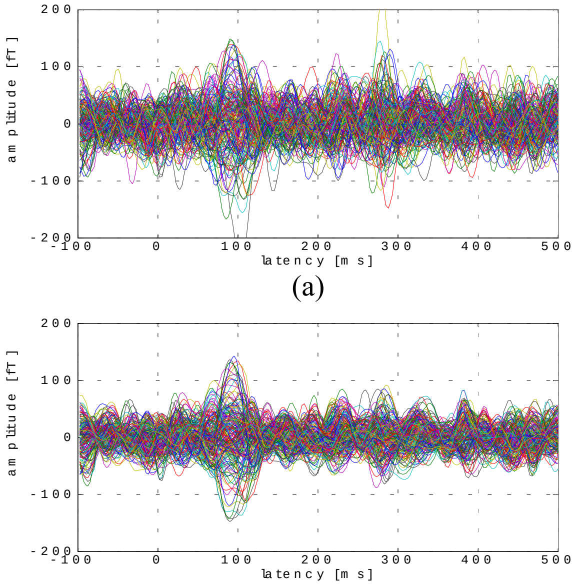
Figure 3: *The waveforms (a) before and (b) after applying this method. The simulated data contains a noise that was obtained by averaging 50 times measured fields (noise level 1). The mean reduction ratio is 21.6 ± 0.8 %*



(a)

(b)

Figure 4: *The waveforms (a) before and (b) after applying this method. The noise field is averaged 20 times (noise level 2). The mean reduction ratio is* 22.9 ± 2.7%



(a)

(b)

Figure 5: *The waveforms (a) before and (b) after applying this method. The noise field is averaged 10 times (noise level 3). The mean reduction ratio is* 23.1 ± 2.7%.

Table 1. *The location errors [mm] for simulation data with noise level 1-3.*

	noise 1 (50)	noise 2 (20)	noise 3 (10)
Ordinary Averaging	3.7 ± 1.5	8.9 ± 3.5	14.5 ± 10.4
After noise reduction	3.0 ± 1.0	7.7 ± 2.7	12.3 ± 8.7

Table 1 shows the location error of the estimated equivalent current dipole.

3.2 Application to MEG data

Figures 6-8 show the waveforms before and after applying this method to AEF data for averaging 50, 20, 10 times.

It is shown that the noise is reduced for which data. However the signal part seems to decrease.

4. Discussion

By applying this method to AEF data (averaging 50, 20, 10), noise reduction of 20-30% was obtained for each AEF data. It was also shown by simulation that this method reduces errors in position estimation for equivalent current dipoles.

The signal-subspace method proposed here can reduce the noise more by combining other theory such as the ICA (independent component analysis) [5].

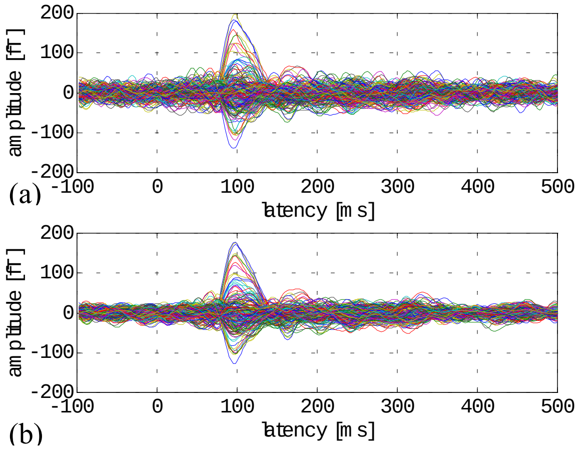


Figure 6: *The waveforms of (a) before applying and (b) after applying this method for averaged 50 times AEF fields. The average of the standard deviations in the baseline (-100 ~ 0 ms) are 10.2[fT] (before) and 8.1[fT] (after).*

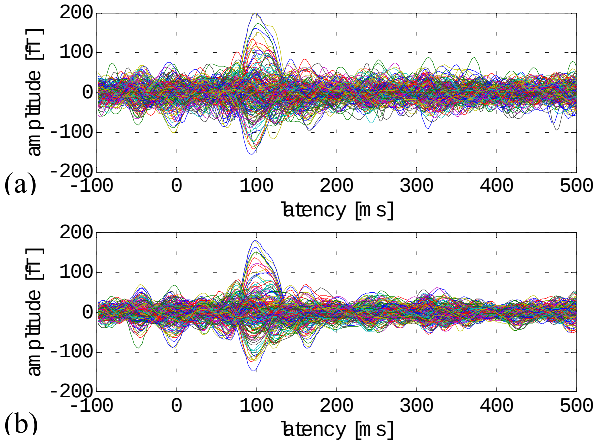


Figure 7: *The waveforms of (a) before applying and (b) after applying this method for averaged 20 times AEF fields.*

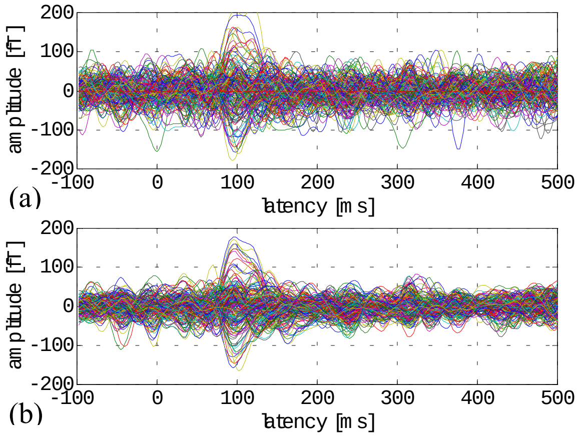


Figure 8. *The waveforms of (a) before applying and (b) after applying this method for averaged 20 times.*

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References

1. T. Kobayashi, S. Kuriki, "Improvement of S/N in evoked neuromagnetic fields by eliminating a spontaneous field component", *Proceedings of 20th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, vol.20, pp.2217-2220, (1998)
2. M. Uusitalo and R.J. Ilmoniemi, "Signal-Space Projection method for separating MEG or EEG into components.", *Med. Biol. Eng. Comp.* **35**, pp. 135-140, (1997).
3. J. Sarvas, "Basic mathematical and electro-magnetic concepts of the biomagnetic inverse problem", *Phys. Med., Biol.***32**, pp.11 – 22, 1987.
4. M. Kawakatsu, K. Kobayashi, Y. Uchikawa, and M. Kotani, "A whole-head 195-channel SQUID MEG system for detecting vector component", in *Recent Advances in Biomagnetism*, T. Yoshimoto, M. Kotani, S. Kuriki, H. Karibe, and N. Nakasato, Eds. Sendai: Tohoku University Press, 1999, pp. 31-34.
5. H. Ishibashi, M. Kawakatsu, M. Adachi, and M. Kotani, "A basic investigation of noise reduction for MEG data using independent function", *this volume.*